

# Higher D or Li: Probes of Physics beyond the Standard Model

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## ABSTRACT

Standard Big Bang Nucleosynthesis at the baryon density determined by the microwave anisotropy spectrum predicts an excess of  ${}^7\text{Li}$  compared to observations by a factor of 4-5. In contrast, BBN predictions for D/H are somewhat below (but within  $2\sigma$ ) of the weighted mean of observationally determined values from quasar absorption systems. Solutions to the  ${}^7\text{Li}$  problem which alter the nuclear processes during or subsequent to BBN, often lead to a significant increase in the deuterium abundance consistent with the highest values of D/H seen in absorption systems. Furthermore, the observed D/H abundances show considerable dispersion. Here, we argue that those systems with  $\text{D}/\text{H} \simeq 4 \times 10^{-5}$  may be more representative of the primordial abundance and as a consequence, those systems with lower D/H would necessarily have been subject to local processes of deuterium destruction. This can be accounted for by models of cosmic chemical evolution able to destroy in situ Deuterium due to the fragility of this isotope.

## 1. Introduction

The importance of  ${}^7\text{Li}$  to cosmology began with the discovery of the Spite plateau (Spite & Spite 1982). At a time when there was still considerable uncertainty in the baryon density, Yang et al. (1984) derived an upper limit to the baryon-to-photon ratio,  $\eta$ , effectively using the  ${}^7\text{Li}/\text{D}$  ratio. Remarkably, the  ${}^7\text{Li}$  plateau has maintained a very constant value over the last 30 years and over many observations, see e.g., (Spite et al. 1984; Spite & Spite 1986; Hobbs & Duncan 1987; Rebolo et al. 1988; Hobbs & Thorburn 1991; Thorburn 1994; Pilachowski et al. 1993; Spite & Spite 1993; Molaro et al. 1995; Bonifacio & Molaro 1997; Ryan et al. 1999; Asplund et al. 2006; Bonifacio et al. 2007; Hosford et al. 2009, 2010; Sbordone et al. 2010; Spite & Spite 2010). While the standard big bang nucleosynthesis (SBBN) predictions for  ${}^7\text{Li}$  abundances have also remained relatively stable (Walker et al. 1991; Olive et al. 2000; Cyburt et al. 2001; Coc et al. 2002, 2004; Cyburt 2004; Cuoco et al. 2004; Cyburt et al. 2008; Iocco et al. 2009; Coc et Vangioni 2010; Coc et al. 2012), the baryon density has been determined to unprecedented precision (Dunkley et al. 2009; Komatsu et al. 2011) from analyses of microwave background anisotropies. This has led to a more precise prediction of the  ${}^7\text{Li}$  abundance that points to a clear discrepancy (Cyburt et al. 2008; Fields 2011) between theory and observation.

At a baryon-to-photon ratio of  $\eta = 6.16 \times 10^{-10}$  (Komatsu et al. 2011), the BBN prediction for  ${}^7\text{Li}/\text{H}$  is  $(5.07^{+0.71}_{-0.62}) \times 10^{-10}$  in Cyburt et al. (2008) and  $5.24 \times 10^{-10}$  in Coc et al. (2012) with an estimated error bar of 0.5, which is considerably higher than almost all observational determinations. The value found in Ryan et al. (2000) was  ${}^7\text{Li}/\text{H} = (1.23^{+0.34}_{-0.16}) \times 10^{-10}$ . Similarly, the recent analysis of Sbordone et al. (2010) found  ${}^7\text{Li}/\text{H} = (1.58 \pm 0.31) \times 10^{-10}$ . Li observations have also been performed in some globular clusters. For example, González Hernández et al. (2009) found  $(2.34 \pm 0.05) \times 10^{-10}$  in NGC 6397, somewhat higher than the result for field stars, whereas Monaco et al. (2010) found a value  ${}^7\text{Li}/\text{H} = (1.48 \pm 0.41) \times 10^{-10}$  in Omega Centauri that is similar to halo star abundances.

Resolution of the  ${}^7\text{Li}$  problem has involved many different approaches. These range from questioning the nuclear reaction rates used in BBN calculations (Coc et al. 2004; Angulo et al. 2005; Cyburt et al. 2004; Boyd et al. 2010), or considering additional resonance reactions (Cyburt & Pospelov 2009; Chakraborty et al. 2011; Broggini et al. 2012). The possibility that depletion plays a role has been discussed at length (Vauclair & Charbonnel 1998; Pinsonneault et al. 1998, 2002; Richard, Michaud & Richer 2005; Korn et al. 2006; García Pérez et al. 2008). The temperature scale used in the  ${}^7\text{Li}$  abundance determination has also been considered (Meléndez & Ramírez 2004; Hosford et al. 2009, 2010). There is also the possibility that the solution of the  ${}^7\text{Li}$  problem requires physics beyond the standard model. For example, the decay of a massive particle during or after BBN could affect

the light element abundances and potentially lower the  ${}^7\text{Li}$  abundance (Jedamzik 2004; Kawasaki et al. 2005; Feng et al. 2004; Ellis et al. 2005; Jedamzik et al. 2006; Cyburt et al. 2006; Kusakabe et al. 2007; Cumberbatch et al. 2007; Kawasaki et al. 2008; Pospelov et al. 2008; Jittoh et al. 2008; Jedamzik & Pospelov 2009; Cyburt et al. 2009; Kusakabe et al. 2008, 2010; Jedamzik 2008a,b; Bailly et al. 2009; Pospelov & Pradler 2010a,b; Cyburt et al. 2010; Jittoh et al. 2010; Kawasaki & Kusakabe 2011). Another possibility raised recently is that of an axion condensate which cools the photon background leading to lower value of  $\eta$  at the time of BBN relative to that determined by WMAP (Erken et al. 2012; Kusakabe et al. 2012). More exotic solutions involve the possibility of a variation in the fundamental constants (Dmitriev et al. 2004; Coc et al. 2007; Berengut et al. 2010).

The problem with  ${}^7\text{Li}$  should be put into context with respect to the other light elements produced in BBN. In particular, there is relatively good agreement between the BBN predictions for  ${}^4\text{He}$  and  $\text{D}/\text{H}$  and their observational determinations. The helium abundance is the most accurately predicted of the primordial abundances. At  $\eta = 6.16 \times 10^{-10}$ , the helium mass fraction is  $Y_p = 0.2483 \pm 0.0002$  (Cyburt et al. (2008)); Coc et al. (2012) found a similar value,  $Y_p = 0.2476 \pm 0.0004$ . On the observational side, the determination of the helium abundance in extragalactic HII regions is plagued with difficulties (Olive & Skillman 2001). Using the Markov Chain-Monte Carlo methods described in Aver et al. (2011) and data compiled in Izotov et al. (2007), Aver et al. (2012) found a higher value with considerably larger uncertainties,  $Y_p = 0.2534 \pm 0.0083$ . Given the uncertainty, this value is consistent with the BBN prediction.

The observationally determined deuterium abundance is also in reasonable agreement with its BBN prediction. There are nine quasar absorption system observations (Burles & Tytler 1998a,b; O’Meara et al. 2001; Pettini & Bowen 2001; Levshakov et al. 2002; Kirkman et al. 2003; O’Meara et al. 2006; Pettini et al. 2008; Fumagalli et al. 2011) with measurable  $\text{D}/\text{H}$  and with a weighted mean abundance of  $3.05 \pm 0.22 \times 10^{-5}$ . This should be compared to the BBN prediction at the WMAP value of  $\eta$  of  $2.54 \pm 0.17 \times 10^{-5}$  from Cyburt et al. (2008) and  $2.59 \times 10^{-5}$  from Coc et al. (2012) with an estimated error of 0.15. The individual measurements of  $\text{D}/\text{H}$  show considerable scatter (a sample variance of 0.62) and it is likely that systematic errors dominate the uncertainties. While the agreement is certainly reasonable, we do draw attention to the fact that the predicted abundance is somewhat *lower* than the observed mean and this (slight) discrepancy will go in the direction of the possible  ${}^7\text{Li}$  solution discussed below.

As might be expected, when one attempts to resolve the  ${}^7\text{Li}$  problem by going beyond the standard model, there may be consequences for the other light elements. Indeed, the destruction of  ${}^7\text{Li}$  is often accompanied by the production of deuterium. In the models we

will consider below, we assume a relatively late decay of a massive particle. Specifically (to be described in more detail in the next section), we consider the decay of a massive gravitino (mass 3-5 TeV) with a life-time of order 100-500 s. The decays eject both hadronic and electromagnetic energy which breaks up a small fraction of  $^4\text{He}$  leading to an increase in the deuterium abundance and free neutrons which destroy the freshly produced  $^7\text{Be}$  from BBN. The models considered here were developed in Cyburt et al. (2009). In Cyburt et al. (2010), the particular part of the parameter space most efficient for destroying  $^7\text{Li}$  was studied and we make use of those results here.

In what follows, we will briefly review the results of post-BBN processing by a late decaying massive particle. We will see a tight correlation between the D/H and  $^7\text{Li}/\text{H}$  abundances. As a result, a solution to the  $^7\text{Li}$  problem will invariably lead to an excess of D/H. However, deuterium can be easily destroyed in stars. In section 3, we first attempt to trace the evolution of these abundances in a model of cosmic chemical evolution based on hierarchical clustering (Daigne et al. 2004, 2006). As we will see, constraints from the cosmic star formation rate will limit the average amount of destruction of both D and Li. Furthermore, we will argue that the observed scatter is probably due to the in situ destruction of D/H. In section 4, we analyze the deuterium data and in section 5 we discuss new and interesting observations of HD/H<sub>2</sub> and the possibility that only those absorption systems with the highest D/H represent the (post)-primordial value.

## 2. Post-BBN processing of the light elements

While there are many possible models which lead to the post-BBN processing of the light elements, we will focus here on a set of supersymmetric models in which there is a massive gravitino which decays into the lightest supersymmetric particle (LSP) which is also a dark matter candidate (Jedamzik 2004; Kawasaki et al. 2005, 2008; Kohri et al. 2006; Cyburt et al. 2009, 2010). In particular, we consider a constrained version of the minimal supersymmetric model which is described by four parameters: a universal gaugino mass,  $m_{1/2}$ ; a universal scalar mass,  $m_0$ ; a universal trilinear term,  $A_0$ ; and the ratio of the two Higgs expectation values,  $\tan\beta$ . In addition, we must specify the sign of the Higgs mixing parameter,  $\mu$ , which take to be positive, and the gravitino mass (see e.g. (Ellis & Olive 2010)).

As we will see, there is very little dependence on the choice of the specific supersymmetric model defined by the parameters  $m_{1/2}$ ,  $m_0$ ,  $A_0$ , and  $\tan\beta$ . However, resulting abundances of D and Li will be quite sensitive to the the gravitino mass and its assumed abundance. We will focus on a small but varied set of benchmark points (Battaglia et al. 2001,

2004; de Roeck et al. 2007) which are defined by  $(m_{1/2}, m_0, \tan \beta) = (400, 90, 10)$  - point C;  $(300, 1615, 10)$  - point E;  $(460, 310, 50)$  - point L;  $(1840, 1400, 50)$  - point M; all with  $A_0 = 0$ . The post-BBN processing of a gravitino decay for each of these benchmark points was studied extensively in Cyburt et al. (2009, 2010) and we make use of those results here.

In the models of interest, gravitinos decay to lighter supersymmetric states, ultimately leading to the lightest neutralino in the final state. For the post-BBN processing of the light elements and the destruction of  ${}^7\text{Li}$ , decays with the injection of hadrons are most important. These occur through gravitino decays to a neutralino + Z, or when kinematically allowed to a chargino + W, and gluino + gluon. Three-body decays which include a quark-antiquark pair may also be important. Subsequent decays of the gravitino decay products (e.g. Z decays) lead to the injection of non-thermal protons and neutrons which may interact with the recently produced light elements.

The dominant primary reaction involving the non-thermal decay products is the photo-erosion and spallation of  ${}^4\text{He}$ . Since  ${}^4\text{He}$  dominates the abundances of the other light elements by many orders of magnitude, even a small amount of destruction (which leaves little trace on the  ${}^4\text{He}$  abundance itself) may induce significant changes in the abundances of the other light elements. Generally, the spallation of  ${}^4\text{He}$  leads to a net increase in the deuterium abundance, as one might expect. The final abundance of  ${}^7\text{Li}$  depends sensitively on the lifetime of the decaying particle. For relatively long lifetimes ( $\gtrsim 10^4$  s), the  ${}^7\text{Li}$  abundance is increased. The  $A=3$  products of  ${}^4\text{He}$  spallation, tritium and  ${}^3\text{He}$  undergo secondary interactions  ${}^3\text{He}(\alpha, \gamma){}^7\text{Be}$  and  $\text{T}(\alpha, \gamma){}^7\text{Li}$ , both of which increase the final  ${}^7\text{Li}$  abundance. For shorter lifetimes, there is a two-step process which leads to the net destruction of  ${}^7\text{Li}$  (Jedamzik 2004). First, thermalized and non-thermal neutrons interact with  ${}^7\text{Be}$  through  ${}^7\text{Be}(n, p){}^7\text{Li}$ , which is followed by  ${}^7\text{Li}(p, \alpha){}^4\text{He}$ .

For each of the four benchmark points, Cyburt et al. (2010) used the observationally determined abundances of  ${}^4\text{He}$ , D/H and  ${}^7\text{Li}/\text{H}$  to find the value of the gravitino mass and abundance which best fit the data. Indeed, it was found that a significant improvement to standard BBN could be achieved with gravitino masses  $m_{3/2} \sim 4 - 5$  TeV with abundances  $\zeta_{3/2} \equiv m_{3/2} n_{3/2} / n_\gamma \sim 5 \times 10^{-11} - 5 \times 10^{-10}$ . With very little dependence on the specific supersymmetric model, the resulting D/H and  ${}^7\text{Li}/\text{H}$  abundances were approximately  $3.2 \times 10^{-5}$  and  $2.4 \times 10^{-10}$  respectively. The resulting D/H and  ${}^7\text{Li}$  abundances for each of the four benchmark models is shown in Figure 1 for gravitino masses in the range 2-5 TeV with abundances  $\zeta_{3/2} = 2.4 \times 10^{-14} - 2.4 \times 10^{-8}$  GeV with cuts:  ${}^7\text{Li}/\text{H} < 4 \times 10^{-10}$  and  $\text{D}/\text{H} < 10^{-4}$ . The best fit point in each case, is shown by a (red) star. While there is considerably more scatter in benchmark point M, the lower envelope in each of the models is clearly very similar.

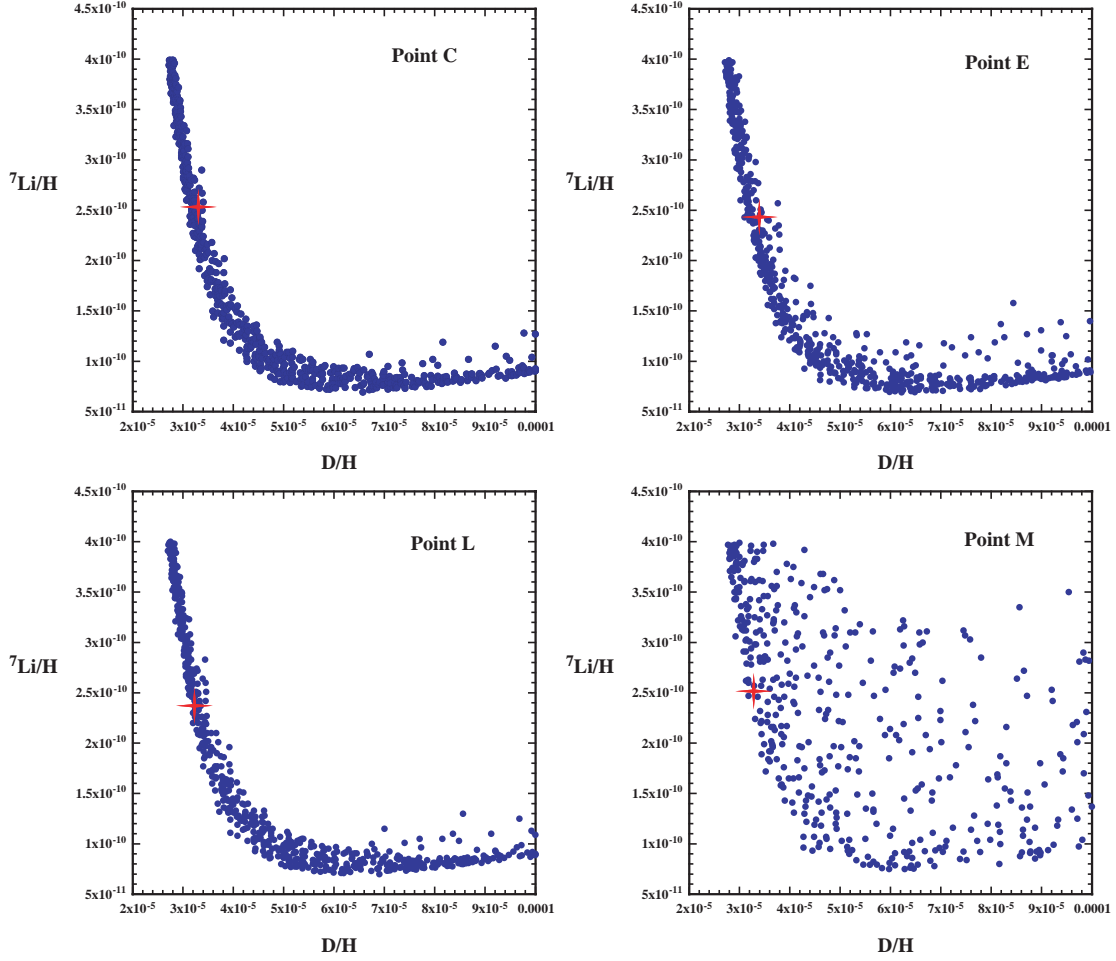


Fig. 1.— The resulting  ${}^7\text{Li}$  abundance as a function of the resulting  $\text{D}/\text{H}$  abundance due to the late decays of a massive gravitino.

While the best fits in each case offer a significant improvement with respect to the observed abundances<sup>1</sup>, from Figure 1, one can see that the  ${}^7\text{Li}$  abundance can be lowered further at the expense of slightly higher  $\text{D}/\text{H}$ . However, the  $\text{D}/\text{H}$  abundance is already relatively high at the best fit points with respect to the weighted mean of  $\text{D}/\text{H}$  as determined from observations of quasar absorption systems as described in the previous section. We next examine the role of cosmic chemical evolution on these abundances and take a critical look as to whether the weighted mean is an appropriate measure of the primordial deuterium

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<sup>1</sup>The  $\chi^2$  based on  ${}^4\text{He}$ ,  $\text{D}/\text{H}$ , and  ${}^7\text{Li}/\text{H}$  for standard BBN is 31.7. In contrast, the  $\chi^2$  for benchmark points C,E,L,M are 5.5, 5.5, 5.4, 7.0 at their respective best fit points (Cyburt et al. 2010).

abundance.

### 3. The effects of cosmic chemical evolution

#### 3.1. Generalities

To follow the cosmic chemical evolution of the light elements along with a metallicity tracer, we use an analytical model developed first by Daigne et al. (2004, 2006), reproducing the cosmic star formation rate in a cosmological context of structure formation. The model is based on the standard Press-Schechter (PS) formalism (Press & Schechter 1974) to account for non linear structures. The rate at which structures accrete mass is determined by a Press-Schechter distribution function,  $f_{PS}(M, z)$ . The model tracks baryons 1) within stars or their remnants within collapsed structures, 2) in gas within collapsed structures (the interstellar medium, ISM), or 3) outside of structures (the intergalactic medium, IGM). The model includes mass (baryon) exchange between the IGM and ISM, and between the ISM and the stellar component. The age  $t$  of the Universe is related to the redshift by

$$\frac{dt}{dz} = \frac{9.78h^{-1} \text{ Gyr}}{(1+z)\sqrt{\Omega_{\Lambda} + \Omega_{\text{m}}(1+z)^3}}, \quad (1)$$

assuming the cosmological parameters of the so-called “concordance model”, with a density of matter  $\Omega_{\text{m}} = 0.27$  and a density of “dark energy”  $\Omega_{\Lambda} = 0.73$  and taking  $H_0 = 71 \text{ km/s/Mpc}$  for the Hubble constant ( $h = 0.71$ ). This allows us to trace all of the quantities we describe as a function of redshift. The input stellar data (lifetimes, mass and type of remnant, metal yields, and UV flux) are taken to be dependent on both the mass and the metallicity of the star (see Daigne et al. (2004) for more detail). Once these parameters are specified, we can follow many other astrophysical quantities such as the global SFR or the abundances of individual elements (Y, D, Li, Fe, O) in the course of the expansion of the universe. This has been used to investigate specific issues related to early star formation and the reionization epoch (Rollinde et al. 2009).

In this study, we will consider a combination of three distinct modes of star formation: a normal mode of Pop II/I, and two additional modes of massive and intermediate mass (IM) Pop III stars (for more detail see Vangioni et al (2011)). Each mode has a specific IMF: between  $0.1 M_{\odot}$  and  $100 M_{\odot}$  for the normal mode of star formation, between  $2 M_{\odot}$  and  $8 M_{\odot}$  for the intermediate mass mode and between  $36 M_{\odot}$  and  $100 M_{\odot}$  for the massive mode ; the slope of the IMF is taken to be close to the Salpeter value ( $x = 1.6$ ).

There are several motivations for including the intermediate mass mode. These stars

may correspond to Pop III.2 stars which originate from material polluted by pristine PopIII.1 stars (Bromm et al. 2009). However, our mass range precludes any type II supernovae (SNe) associated with this mode of star formation. In addition, there are theoretical arguments that the metal-free IMF predicted from opacity-limited fragmentation theory would peak around  $4 - 10 M_{\odot}$  with steep declines at both larger and smaller masses (Yoshii & Saio 1986). Primordial CMB regulated-star formation may also lead to the production of a population of early intermediate mass stars at low metallicity (Smith et al. 2009; Schneider & Omukai 2010; Safranek-Shrader et al. 2010).

There is considerable evidence for an early contribution by IM stars from observations. These stars produce very little in the way of heavy elements (oxygen and above), but produce significant amounts of carbon and/or nitrogen and above all helium. Evidence exists that the number of carbon-enhanced stars increases at low iron abundances (Rossi et al. 1999) necessitating a Pop III source of carbon, possibly in the asymptotic giant branch (AGB) phase of IM stars (Fujimoto et al. 2000; Aoki et al. 2002; Lucatello et al. 2005) indicating possibly an IMF peaked at  $4 - 10 M_{\odot}$  (Abia et al. 2001). In addition, the presence of s-process elements, particularly Pb at very low metallicity also points to AGB enrichment very early on (Aoki et al. 2001; Sivarani et al. 2004).

Isotopic studies of Mg also show a need for an early generation of IM stars. While core collapse supernovae produce almost exclusively  $^{24}\text{Mg}$ , observations of Yong et al. (2003a,b); Alibés et al. (2001); Fenner et al. (2003) show enhancements (relative to predictions based on standard chemical evolution models) in both  $^{25,26}\text{Mg}$ . Finally, IM stars may in part be responsible for the somewhat high  $^4\text{He}$  abundances seen in low metallicity dwarf galaxies (Vangioni et al 2011). Our motivation here for considering an early population of IM stars is clear: they offer the possibility for destroying significant amounts of Deuterium without producing heavy elements (Fields et al 2001).

We fit the SFR history of Pop II/I stars to the data compiled in Hopkins & Beacom (2006) (from  $z = 0$  to 5), and to the recent measurements at high redshift by Bouwens et al. (2010) and Gonzalez et al. (2010). This is modeled by the expression suggested by Springel and Hernquist (2003) :

$$\psi(z) = \nu \frac{a \exp(b(z - z_m))}{a - b + b \exp(a(z - z_m))}, \quad (2)$$

where  $\nu$  and  $z_m$  are the amplitude (astration rate) and the redshift of maximum SFR respectively; and  $b$  and  $b - a$  are related to the slopes of the curve at low and high redshifts respectively. The normal mode is fit using:  $\nu_{\text{II/I}} = 0.3 M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$ ,  $z_{\text{m II/I}} = 2.6$ ,  $a_{\text{II/I}} = 1.9$  and  $b_{\text{II/I}} = 1.1$ . The SFR of this mode peaks at  $z \approx 3$ . These observations place strong constraints on the Pop II/I SFR.

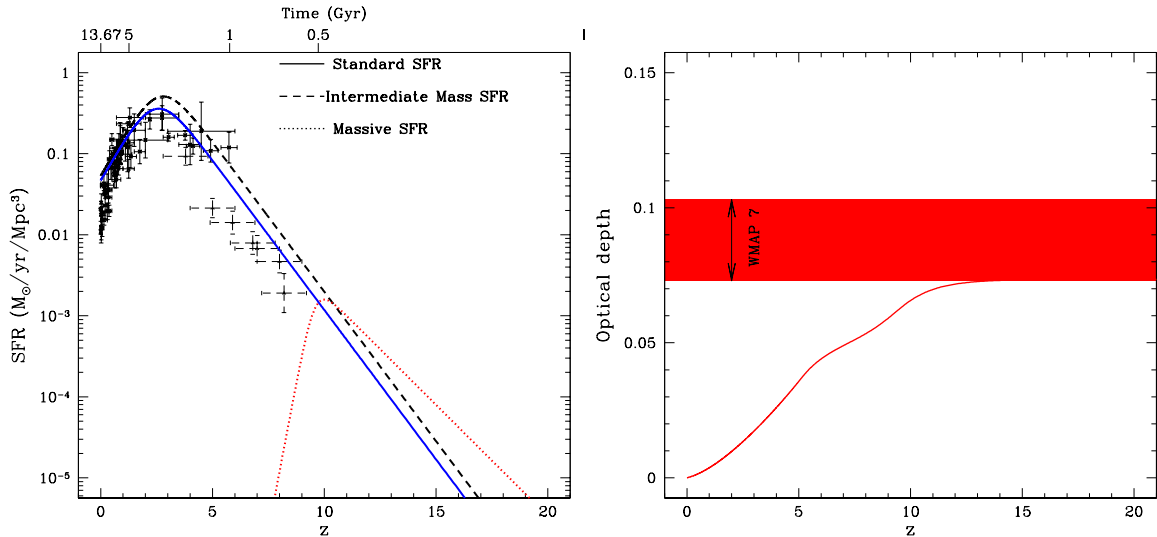


Fig. 2.— *Left panel:* Cosmic star formation rate (SFR) as a function of redshift. The data (solid black points and solid error bars) are taken from Hopkins & Beacom (2006). Dashed black error bars correspond to results by Bouwens et al. (2010) and Gonzalez et al. (2010). The blue solid line represents the normal SFR mode with a Salpeter IMF and a mass range:  $0.1 < M/M_{\odot} < 100$ . The dotted red line represents the massive Pop III stellar mode with a mass range:  $36 < M/M_{\odot} < 100$ . The dashed black curve represents the intermediate mass SFR mode,  $2 < M/M_{\odot} < 8$ . *Right panel:* the optical depth deduced from WMAP observations is presented as a function of the redshift. The red range corresponds to the observed results from WMAP7 (Komatsu et al. (2011)). The red line corresponds to the model including all SFR modes.

As noted above, in addition to the normal mode, we add two modes for Pop III stars. The IM (massive) SFR parameters are:  $\nu_{\text{IIIa}} = 0.4(0.7) M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$ ,  $z_{\text{m IIIa}} = 2.8(10.)$ ,  $a_{\text{IIIa}} = 1.9(4)$  and  $b_{\text{IIIa}} = 1.1(3.3)$ . Parameters are chosen to maximize the potential for D/H astration (without the production of heavy elements) while remaining concordant with the observed SFR at high redshift. For a detailed description of the model see Rollinde et al. (2009) and Daigne et al. (2006). A recent study shows that the first stars have feedback-limited masses of around  $40 M_{\odot}$  (Hosokawa et al. 2011), appropriate for core-collapse supernovae.

In Figure 2, we show the adopted SFR for each of the three modes considered. As one can see, the normal mode and the intermediate mass SFR are constrained to fit the observations plotted in the figure. As the data extend only up to  $z \approx 8$ , there is little constraint

for  $z > 8$ . Indeed, data at these redshifts are highly uncertain due to unknown systematics involving, among other effects, dust correction and adopted rest-frame UV luminosity function (Labbe et al. 2010). In this context, the massive mode which can dominate at  $z \gtrsim 10$  is constrained to fit the optical depth deduced from WMAP observations (shown in the right panel of Figure 2 ). The global SFR used in this study is the sum of these three modes.

### 3.2. The cosmic evolution of D and Li

In the cosmological context described above, it is possible to track the evolution of both light elements, D and  ${}^7\text{Li}$ . Following the analysis of Section 2 corresponding to the post-BBN processing of the light elements, we consider the resulting D and  ${}^7\text{Li}$  abundances due to the late decays of a massive gravitino (see Figure 1). As noted earlier, a general consequence of lowering  ${}^7\text{Li}$  is higher D/H. So to fit the Spite plateau we choose three representative values for the  ${}^7\text{Li}$  abundance corresponding to the values quoted in the introduction:  ${}^7\text{Li}/\text{H} = 1.23 \times 10^{-10}$ ,  $1.58 \times 10^{-10}$ , and  $2.34 \times 10^{-10}$ . These abundances correspond to  $\text{D}/\text{H} = 4.4 \times 10^{-5}$ ,  $3.9 \times 10^{-5}$ , and  $3.3 \times 10^{-5}$  respectively.

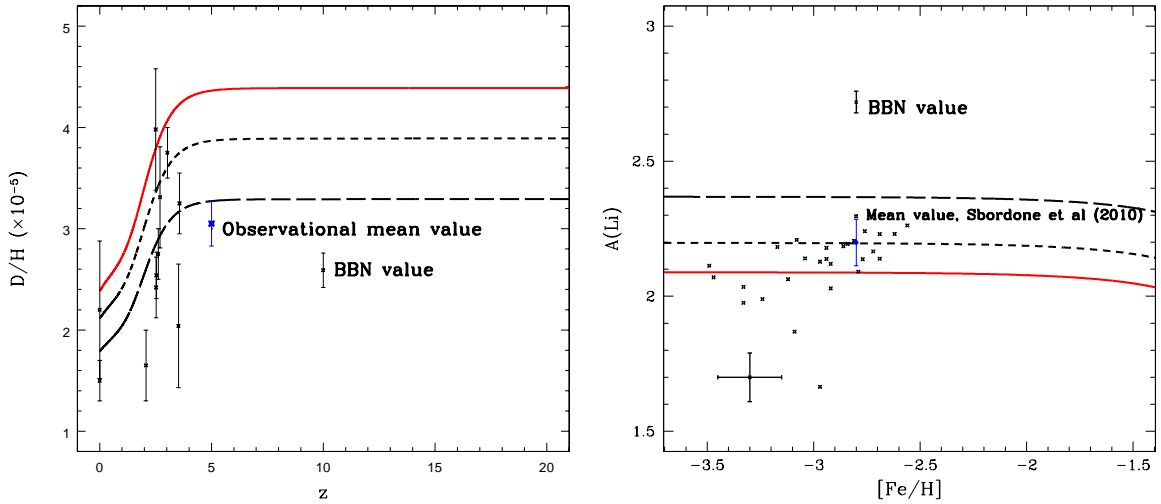


Fig. 3.—  $\text{D}/\text{H}$  abundance as a function of redshift (left) and  $A(\text{Li}) = \log(\text{Li}/\text{H}) + 12$  as a function of  $[\text{Fe}/\text{H}]$  (right). Deuterium data come from observations described in the text. Lithium data come from (Sbordone et al. 2010). The red solid (black short dashed and large dashed) lines correspond to initial post-BBN  $\text{Li}/\text{H}$ ,  $\text{D}/\text{H}$  values:  $1.23 \times 10^{-10}$ ,  $4.4 \times 10^{-5}$ ,  $(1.58 \times 10^{-10}, 3.9 \times 10^{-5})$ , and  $2.34 \times 10^{-10}, 3.3 \times 10^{-5}$  respectively.

In Figure 3 we show the cosmic evolution of lithium as a function of metallicity and the corresponding D/H evolution as a function of redshift in the three selected cases. At the metallicities of interest, there is very little evolution in the  ${}^7\text{Li}$  abundance. The high redshift Deuterium data come from observations discussed in the next section. The local Deuterium data ( $z = 0$ ) is taken from Linsky et al. (2006) in the Local Bubble and the higher value from Savage et al. (2007) in the warm neutral medium of the Galactic halo. D destruction begins at redshift 3, corresponding to the peak of the cosmic SFR (see figure 2, left). The global evolution of D/H fits the observations reasonably well, given the observational uncertainties (see next Section for a discussion).

It is important to note the high dispersion of the observed values at  $z \sim 3$  (corresponding to  $t = 3\text{--}4$  Gyr) in the range  $2.4 - 4. \times 10^{-5}$ . This could be a consequence of different star formation histories in the galaxies associated with the DLAs. Note that the individual chemical evolution histories are not probed by our model of cosmic chemical evolution which only yields the average abundances of the elements in structures and in the IGM. However, D is a very fragile isotope (it is destroyed in stars at  $T = 10^5$  K) and its destruction rate is highly dependent on the ratio  $\sigma = \text{gas mass}/\text{total mass}$  of the galaxy as shown in Vangioni & Audouze (1988) (see their figure 3); a low ratio corresponding to a low D abundance. As a consequence, D/H destruction factors can range between 2 to 10. Indeed, Fields et al (2001) showed that D can be efficiently destroyed without overproducing metals in a standard chemical evolutionary model with an early population of intermediate mass stars (see their figure 1). It is reasonable to think that these pristine structures are in different evolution stages and consequently have different gas masses and processing histories. Finally, as D can only be destroyed in the course of chemical evolution (Epstein et al. 1976), it is reasonable to relate the highest D/H observation to the primordial post-BBN abundance. In this context, we are able to reconcile the BBN D abundance and high D/H observational values at high redshift together with theoretical and observational Li abundances.

#### 4. Analysis of the D/H observations

Most of the measurements available in the literature have been gathered by Pettini et al. (2008) and more recently in Fumagalli et al. (2011). It was concluded, however, that the measurements by Levshakov et al. (2002) and Crighton et al. (2004) are not relevant because not all of the D I components in those observations are resolved. This effect would imply systematically low D/H if one has included velocity components in H I that are not detected in D I because the D I is hidden by other H I absorption features (Kirkman et al. 2003).

Levshakov et al. (2002) convincingly showed that D I is detected at  $z = 3.03$  toward Q 0347–3819 in the transitions Ly-8, 10 and 12 (see their Fig. 12). They fit the D I absorption with a profile that is consistent with the N I and O I profiles. Although the latter is saturated, the former is well defined in N I  $\lambda\lambda 953.4, 964.0$  (see their Fig. 10). The high D I/H I value derives from the presence of a narrow component with Doppler parameter as small as  $\sim 3 \text{ km s}^{-1}$ . The presence of this narrow component is well demonstrated however by the detection of H<sub>2</sub> in a single component. Thirty one H<sub>2</sub> transitions are used to derive the Doppler parameter from the curve of growth (see their Fig. 3). In addition the H<sub>2</sub> excitation diagram indicates a temperature of  $\sim 825 \text{ K}$  which is consistent, within errors, with the low value of the Doppler parameter. The temperature found here is also consistent with the findings that the molecular fraction is small in most DLAs because the gas is warm (Petitjean et al. 2006). Although errors may have been underestimated (see Appendix of Kirkman et al. (2003), there is no objective reason to reject this measurement,  $\text{D/H} = (3.75 \pm 0.25) \times 10^{-5}$  for  $\log N(\text{H I}) = 20.56 \pm 0.05$  and  $\text{Zn/H} = 0.98 \pm 0.09$  (Ledoux et al. 2003). Thus, we have included this value in our study. Note that D’Odorico et al. (2001) report a lower value in this system:  $\text{D/H} = 2.24 \pm 0.67 \times 10^{-5}$ , but their  $b$  values are certainly too large and their value should be considered as a lower limit.

Crichton et al. (2004) reported  $\text{D/H} = 1.6^{+0.25}_{-0.3} \times 10^{-5}$  towards PKS 1937–1009 in a Lyman Limit System (LLS) with  $\log N(\text{H I}) = 18.25 \pm 0.02$  and for a metallicity of  $[\text{Si/H}] = -2.0 \pm 0.5$  at  $z = 3.256$ . In that case only Lyman- $\alpha$  and Lyman- $\beta$  lines are used and indeed, a model with lower H I and higher D I column densities can be accommodated (see O’Meara et al. (2006)). As a result, we have not included this reported measurement in our analysis.

In addition, it is surprising that Pettini et al. (2008) do not consider the measurement by Levshakov et al. (2002) when they retain the measurement at  $z = 2.06$  towards Q 2206–199 which is obtained from a low SNR intermediate resolution ( $R \sim 15000$ ) STIS-HST spectrum (see discussion in the Appendix of Kirkman et al. (2003)). Furthermore, the  $b$  value and the decomposition of the profile are uncertain in this observation and the D/H ratio has been claimed to be possibly as high as  $2.9 \times 10^{-5}$  (see (Kirkman et al. 2003)). While we retain this object in our average, we comment as well on the effect of excluding it.

Very recently, Fumagalli et al. (2011) measure  $\log (\text{D/H}) = -4.69 \pm 0.13$  in a LLS ( $\log N(\text{H I}) = 17.95$ ) at  $z = 3.522$  towards SDSS J113418.96+574204.6. They argue that the gas is pristine with metallicity  $< 10^{-4.2}$  solar. However, at such a low neutral hydrogen column density, the gas is most probably partially ionized and a correction for ionization effects has to be applied. To reach their conclusion, they assume a value for the ionization parameter ( $\log U > -3$ ) and argue that a gas density larger than  $n_{\text{H}} > 10^{-2} \text{ cm}^{-3}$  is unusual in LLSs. We believe that this assumption is unjustified and a density of  $n_{\text{H}} \sim 10^{-1} \text{ cm}^{-3}$

is perfectly acceptable (see e.g. Petitjean et al. (1992)). Therefore a robust upper limit on the metallicity is not less than  $10^{-3}$  solar. This abundance is typical of what is found for Damped Lyman  $\alpha$  Systems (DLAs) with the smallest observed metallicities (Penprase et al. 2011; Cooke et al. 2011). Therefore, the gas may not be pristine and the low value of the D/H ratio could be a consequence of deuterium destruction by star formation activity.

Consequently, we have included all deuterium measurements from Pettini et al. (2008) plus the measurements by Levshakov et al. (2002) and the recent report in Fumagalli et al. (2011). The weighted mean of these nine measurements is  $D/H = (3.05 \pm 0.22) \times 10^{-5}$ , where a scale factor of  $S = 2.0$  ( $= \sqrt{\chi^2/8}$ ) is applied to the error in the mean to partially account for the large dispersion. The sample variance would imply a much larger uncertainty of  $0.62 \times 10^{-5}$ . We note that this value is in modest *disagreement* with the SBBN value of  $2.54 \pm 0.17 \times 10^{-5}$  from Cyburt et al. (2008) or  $2.59 \pm 0.15 \times 10^{-5}$  from Coc et al. (2012). Excluding the data from Levshakov et al. (2002), we find  $D/H = (2.80 \pm 0.20) \times 10^{-5}$  ( $S = 1.64$ ) and a sample variance of  $(0.52 \times 10^{-5})$  for eight objects. Neglecting instead the data from Pettini & Bowen (2001), we find  $D/H = (3.11 \pm 0.21) \times 10^{-5}$  ( $S = 1.83$ ) and a sample variance of  $(0.55 \times 10^{-5})$ , also for eight objects.

It has already been noted by several authors that the dispersion in the reported D/H-values is much larger than what is expected from individual errors. This could be a consequence of the errors having been underestimated. The presumption of a unique value for D/H, however, is not supported by the observations (see also Ivanchik et al. (2010)). Furthermore, if the post-BBN value for D/H were at or near the upper end of the existing data as in Figure 3, the dispersion seen in the data could be explained by the in situ destruction of D/H through chemical evolution. If this is indeed a local effect, the extent of the dispersion is not surprising.

## 5. Discussion

As mentioned in the Introduction, there are many potential solutions to the SBBN  ${}^7\text{Li}$  problem. It is fair to say that all of them require some additional input beyond what we normal term as standard. This may involve additional turbulent features in diffusive models of stellar evolution (Korn et al. 2006) or new resonant reactions (Cyburt & Pospelov 2009; Chakraborty et al. 2011; Broggini et al. 2012). However, several of the possible solution come with the price of an increased D/H abundance: photon cooling (Erken et al. 2012; Kusakabe et al. 2012), variable fundamental constants (Dmitriev et al. 2004; Coc et al. 2007; Berengut et al. 2010) and particle decays during or after BBN (Jedamzik 2004; Kawasaki et al. 2005; Feng et al. 2004; Ellis et al. 2005; Jedamzik et al. 2006; Cyburt et al. 2006; Kusakabe et al.

2007; Cumberbatch et al. 2007; Kawasaki et al. 2008; Pospelov et al. 2008; Jittoh et al. 2008; Jedamzik & Pospelov 2009; Cyburt et al. 2009; Kusakabe et al. 2008, 2010; Jedamzik 2008a,b; Baily et al. 2009; Pospelov & Pradler 2010a,b; Cyburt et al. 2010; Jittoh et al. 2010; Kawasaki & Kusakabe 2011) all tend to increase D/H while yielding a  ${}^7\text{Li}$  abundance which matches the low metallicity Pop II abundance determinations. Here, we have used the results of Cyburt et al. (2010) for the specific correlations between the post-BBN D/H and  ${}^7\text{Li}/\text{H}$  abundances as displayed in Figure 1.

Since the D/H abundance is expected to decrease monotonically over time, a high value of D/H from BBN is not necessarily problematic. First of all, we emphasize that SBBN predicts a value of D/H which is about  $2\sigma$  below the weighted mean of observational determinations. Second, while the post-BBN abundance of D/H may exceed the observational value, we expect some destruction of deuterium due to chemical evolution. Indeed in a model based on hierarchical clustering, we have seen that there is some modest astration of D/H while leaving  ${}^7\text{Li}$  virtually unperturbed as seen in Figure 3. However, because these models yield average abundances, they can not account for the observed dispersion seen in the data. As noted above, this may be due to either under-estimated errors or the in situ destruction of D/H.

Before concluding, we note that the HD/H<sub>2</sub> ratio is an interesting alternative for D/H investigations in DLAs. In the diffuse ISM, with physical conditions very similar to those of DLAs, the formation of HD occurs via the reaction:  $\text{H}_2 + \text{D}^+ \rightarrow \text{HD} + \text{H}^+$  while its destruction is due to photodissociation. Because of the low abundance of deuterium, the transition between atomic deuterium and HD takes place deeper in a cloud than the transition between atomic and molecular hydrogen. Moreover, while the H<sub>2</sub> column density is usually very well constrained by the presence of numerous transitions, only a few transitions are seen for HD, making these measurements quite uncertain. Therefore, although the ratio should be interpreted with care (e.g. Tumlinson et al. (2010)),  $N(\text{HD})/2N(\text{H}_2)$  in the cloud should give a lower limit on the D/H ratio (see Lacour, et al. (2005)).

Molecular hydrogen is found in less than 10% of DLAs (Ledoux et al. 2003; Noterdaeme et al. 2008a) and to date, only five detections of HD at high redshift have been reported. Interestingly, some high D/H values are observed despite significant metal enrichment:  $N(\text{HD})/2N(\text{H}_2) = 1.5 \times 10^{-5}$ ,  $3.6 \times 10^{-5}$ ,  $7.9 \times 10^{-5}$ ,  $1.6 \times 10^{-5}$  and  $0.95 \times 10^{-5}$  at  $z_{\text{abs}} = 2.42$ , 2.33, 2.10, 2.63, and 2.69 towards, J 1439+1117 (Noterdaeme et al. 2008a), Q 1232+082 (Ivanchik et al. 2010), J 2123–0500, FJ 0812+32 (Tumlinson et al. 2010) and SDSSJ 123714.60+064759.5 (Noterdaeme et al. 2008b) for metallicities relative to solar  $[\text{X}/\text{H}] = +0.16$ ,  $-1.43$ ,  $+0.36$ ,  $-0.48$  and  $+0.34$  respectively.

It is apparent that these measurements, although uncertain, are all consistent with the

cosmological D/H ratio and, more importantly, a factor of ten above what is measured in our Galaxy (Lacour, et al. 2005). This finding is somewhat puzzling, in light of the diversity in the other properties of these systems and in particular their high metallicity. Infall of primordial gas can help maintain such high D/H ratios in the course of galactic evolution (e.g., Prodanović & Fields (2008)). However, such process may have difficulties alone to explain the observations. Consequently, these  $HD/H_2$  observations seem to indicate that D/H values at high redshift are somewhat high; indicating again that a high primordial deuterium value is privileged.

In conclusion, we have argued that although many models which are capable of reducing the high BBN abundance of  $^7\text{Li}$  to the level seen in Pop II halo stars come with a price of an increase in the D/H abundance, this may well be a feature and not a bug. The weighed mean of the D/H abundance data (modestly) exceeds the SBBN value, and carries considerable dispersion. If the upper envelope of this data reflects the post-BBN abundance of D/H, then these models which attempt to resolve the  $^7\text{Li}$  problem are preferred. The dispersion seen (if real) must then be explained by the astration of D/H in local processes. We note in closing that non-standard model explanations of the primordial  $^7\text{Li}$  abundance generically predict  $^6\text{Li}$  in excess of the standard model prediction as well as an increase in the deuterium abundance. Confirmation of  $^6\text{Li}$  in extremely metal-poor halo stars would provide significant support for models in which nuclear processes during or subsequent to BBN resolve the  $^7\text{Li}$  problem.

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## REFERENCES

- Abia, C., Domínguez, I., Straniero, O., Limongi, M., Chieffi, A., & Isern, J. 2001, ApJ, 557, 126
- Alibés, A., Labay, J., & Canal, R. 2001, A&A, 370, 1103
- Angulo, C., Casarejos, E., Couder, M., *et al.* 2005, ApJ, 630, L105
- Aoki, W., *et al.* 2001, ApJ, 561, 346
- Aoki, W., Norris, J. E., Ryan, S. G., Beers, T. C., & Ando, H. 2002, ApJ, 567, 1166

- Asplund, M., Lambert, D. L., Nissen, P. E., Primas, F., & Smith, V. V. 2006, *ApJ*, 644, 229
- Aver, E., Olive, K. A., & Skillman, E. D. 2011, *J. Cosmology Astropart. Phys.*, 3, 43
- Aver, E., Olive, K. A., & Skillman, E. D. 2011, *arXiv:1112.3713*
- Bailly, S., Jedamzik, K., & Moulataka, G. 2009, *Phys. Rev. D*, 80, 063509
- Battaglia, M., de Roeck, A., Ellis, J., et al. 2001, *European Physical Journal C*, 22, 535
- Battaglia, M., Roeck, A. D., Ellis, J., et al. 2004, *European Physical Journal C*, 33, 273
- Berengut, J. C., Flambaum, V. V., & Dmitriev, V. F. 2010, *Physics Letters B*, 683, 114
- Bonifacio, P. & Molaro, P. 1997, *MNRAS*, 285, 847
- Bonifacio, P., Molaro, P., Sivarani, T., Cayrel, R., Spite, M., Spite, F., Plez, B., Andersen, J., Barbuy, B., Beers, T. C., Depagne, E., Hill, V., François, P., Nordström, & Primas, F. 2007, *A&A*, 462, 851
- Bouwens, R.J. *et al.* 2010, *ApJL* 709, L133
- Boyd, R. N., Brune, C. R., Fuller, G. M., & Smith, C. J. 2010, *Phys. Rev. D*, 82, 105005
- Broggini, C., Canton, L., Fiorentini, G., & Villante, F. L. 2012, *arXiv:1202.5232*
- Bromm, V., Yoshida, N., Hernquist, L., & McKee, C. F. 2009, *Nature*, 459, 49
- Burles, S., & Tytler, D. 1998a, *ApJ* 499,699
- Burles, S., & Tytler, D. 1998b, *ApJ* 507, 732
- Chakraborty, N., Fields, B. D., & Olive, K. A. 2011, *Phys. Rev. D*, 83, 063006
- Coc, A., & Vangioni, E. 2010, *J. Phys.Conf. Ser.* 202, 012001
- Coc, A., Goriely, S., Xu, Y., Saimpert, M., & Vangioni, E. 2012, *ApJ* 744, 158
- Coc, A., Nunes, N. J., Olive, K. A., Uzan, J.-P., & Vangioni, E. 2007, *Phys. Rev. D*, 76, 023511
- Coc, A., Vangioni-Flam, E., Cassé, M., & Rabiet, M. 2002, *Phys. Rev. D*, 65, 043510
- Coc, A., Vangioni-Flam, E., Descouvemont, P., Adahchour, A. & Angulo, C., 2004, *ApJ*, 600, 544

- Cooke, R., Pettini, M., Steidel, C. C., Rudie, G. C., & Nissen, P. E. 2011, *MNRAS*, 417, 1534
- Crichton, N. H. M., Webb, J. K., Ortiz-Gil, A., Fernandez–Soto, A. 2004, *MNRAS*, 355, 1042
- Cumberbatch, D., Ichikawa, K., Kawasaki, M., et al. 2007, *Phys. Rev. D*, 76, 123005
- Cuoco, A., Iocco, F., Mangano, G., et al. 2004, *International Journal of Modern Physics A*, 19, 4431
- Cyburt, R. H. 2004, *Phys. Rev. D*, 70, 023505
- Cyburt, R. H., Ellis, J., Fields, B. D., Olive, K. A., & Spanos, V. C. 2006, *Journal of Cosmology and Astro-Particle Physics*, 11, 14
- Cyburt, R. H., Ellis, J., Fields, B. D., et al. 2009, *J. Cosmology Astropart. Phys.*, 10, 21
- Cyburt, R. H., Ellis, J., Fields, B. D., et al. 2010, *J. Cosmology Astropart. Phys.*, 10, 32
- Cyburt, R. H., Fields, B. D., & Olive, K. A. 2001, *New Astronomy*, 6, 215
- Cyburt, R. H., Fields, B. D., & Olive, K. A. 2004, *Phys. Rev. D*, 69, 123519
- Cyburt, R. H., Fields, B. D., & Olive, K. A. 2008, *J. Cosmology Astropart. Phys.*, 11, 12
- Cyburt, R. H., & Pospelov, M. 2009, *arXiv:0906.4373*
- Daigne, F., Olive, K. A., Vangioni-Flam, E., Silk, J., & Audouze, J. 2004, *ApJ*, 617, 693
- Daigne, F., Olive, K. A., Silk, J., Stoeck, F., & Vangioni, E. 2006, *ApJ*, 647, 773
- de Roeck, A., Ellis, J., Gianotti, F., et al. 2007, *European Physical Journal C*, 49, 1041
- D’Odorico, S., Dessauges-Zavadsky, M., & Molaro, P. 2001, *A&A*, 368, L21
- Dmitriev, V. F., Flambaum, V. V., & Webb, J. K. 2004, *Phys. Rev. D*, 69, 063506
- Dunkley, J., Komatsu, E., Nolte, M. R., et al. 2009, *ApJS*, 180, 306
- Ellis, J., & Olive, K. A. 2010, *Particle Dark Matter : Observations, Models and Searches*, 142
- Ellis, J., Olive, K. A., & Vangioni, E. 2005, *Physics Letters B*, 619, 30
- Epstein, R. I., Lattimer, J. M., & Schramm, D. N. 1976, *Nature*, 263, 198

- Erken, O., Sikivie, P., Tam, H., & Yang, Q. 2012, *Physical Review Letters*, 108, 061304
- Feng, J. L., Su, S., & Takayama, F. 2004, *Phys. Rev. D*, 70, 075019
- Fenner, Y., Gibson, B. K., Lee, H.-C., Karakas, A. I., Lattanzio, J. C., Chieffi, A., Limongi, M., & Yong, D. 2003, *PASA*, 20, 340
- Fields, B. D. 2011, *Annual Review of Nuclear and Particle Science*, 61, 47
- Fields, B.D. et al 2001, *ApJ*, 563, 653
- Fujimoto, M. Y., Ikeda, Y., & Iben, I., Jr. 2000, *ApJ*, 529, L25
- Fumagalli, M., O’Meara, J. M., & Prochaska, J. X. 2011, arXiv:1111.2334
- García Pérez, A. E., Inoue, S., Aoki, W., & Ryan, S. G. 2008, *Precision Spectroscopy in Astrophysics*, *Proceedings of the ESO/Lisbon/Aveiro Conference*, 9
- González Hernández, J. I., Bonifacio, P., Caffau, E., et al. 2009, *A&A*, 505, L13
- Gonzalez, V. *et al.* 2010, *ApJ*, 713, 115
- Hobbs, L. M., & Duncan, D. K. 1987, *ApJ*, 317, 796
- Hobbs, L. M., & Thorburn, J. A. 1991, *ApJ*, 375, 116
- Hopkins, A.M. and Beacom, J.F. 2006, *ApJ*, 651, 142
- Hosford, A., Ryan, S. G., García Pérez, A. E., Norris, J. E., & Olive, K. A. 2009, *A&A*, 493, 601
- Hosford, A., García Pérez, A. E., Collet, R., Ryan, S. G., Norris, J. E., & Olive, K. A. 2010, *A&A*, 511, 47
- Hosokawa, T., Omukai, K., Yoshida, N. and Yorke, H. 2011, *Science*, 334, 1250
- Iocco, F., Mangano, G., Miele, G., Pisanti, O., & Serpico, P. D. 2009, *Phys. Rep.*, 472, 1
- Ivanchik, A. V., Petitjean, P., Balashev, S. A., Srianand, R., Varshalovich, D. A., Ledoux, C., & Noterdaeme, P. 2010, *MNRAS*, 404, 1583
- Izotov, Y. I., Thuan, T. X., & Stasińska, G. 2007, *ApJ*, 662, 15
- Jedamzik, K. 2004, *Phys. Rev. D*, 70, 063524

- Jedamzik, K., Choi, K.-Y., Roszkowski, L., & Ruiz de Austri, R. 2006, *Journal of Cosmology and Astro-Particle Physics*, 7, 7
- Jedamzik, K. 2008a, *Phys. Rev. D*, 77, 063524
- Jedamzik, K. 2008b, *J. Cosmology Astropart. Phys.*, 3, 8
- Jedamzik, K., & Pospelov, M. 2009, *New Journal of Physics*, 11, 105028
- Jittoh, T., Kohri, K., Koike, M., et al. 2008, *Phys. Rev. D*, 78, 055007
- Jittoh, T., Kohri, K., Koike, M., et al. 2010, *Phys. Rev. D*, 82, 115030
- Kawasaki, M., Kohri, K., & Moroi, T. 2005, *Phys. Rev. D*, 71, 083502
- Kawasaki, M., Kohri, K., Moroi, T., & Yotsuyanagi, A. 2008, *Phys. Rev. D*, 78, 065011
- Kawasaki, M., & Kusakabe, M. 2011, *Phys. Rev. D*, 83, 055011
- Kirkman, D., Tytler, D., Suzuki, N., O’Meara, J. M., & Lubin, D. 2003, *ApJS*, 149, 1
- Kohri, K., Moroi, T., & Yotsuyanagi, A. 2006, *Phys. Rev. D*, 73, 123511
- Komatsu, E., Smith, K. M., Dunkley, J., et al. 2011, *ApJS*, 192, 18
- Korn, A. J., Grundahl, F., Richard, O., Barklem, P. S., Mashonkina, L., Collet, R., Piskunov, N., & Gustafsson B. 2006, *Nature*, 442, 657
- Kusakabe, M., Kajino, T., Boyd, R. N., Yoshida, T., & Mathews, G. J. 2007, *Phys. Rev. D*, 76, 121302
- Kusakabe, M., Kajino, T., Boyd, R. N., Yoshida, T., & Mathews, G. J. 2008, *ApJ*, 680, 846
- Kusakabe, M., Kajino, T., Yoshida, T., & Mathews, G. J. 2010, *Phys. Rev. D*, 81, 083521
- Kusakabe, M., Balantekin, A. B., Kajino, T., & Pehlivan, Y. 2012, *arXiv:1202.5603*
- Labbe, I., Gonzalez, V. & Bouwens, R. J. 2010, *ApJL*, 716, 103
- Lacour, S., André, M. K., Sonnentrucker, P., Le Petit, F., Welty, D. E., Desert, J.-M., Ferlet, R., Roueff, E., & York, D. G. 2005, *A&A*, 430, 967
- Ledoux, C., Petitjean, P., & Srianand, R. 2003, *A&A*, 346, 209
- Levshakov, S. A., Dessauges–Zavadsky, M., D’Odorico, S., & Molaro, P. 2002, *ApJ*, 565, 696

- Linsky, J. L., Draine, B. T., Moos, H. W., et al. 2006, ApJ, 647, 1106
- Lucatello, S., Tsangarides, S., Beers, T. C., Carretta, E., Gratton, R. G., & Ryan, S. G. 2005, ApJ, 625, 825
- Meléndez, J., & Ramírez, I. 2004, ApJ, 615, L33
- Molaro, P., Primas, F., & Bonifacio, P. 1995, A&A, 295, L47
- Monaco *et al.* 2010, A&A , 519, L3
- Noterdaeme, P., Ledoux, C., Petitjean, P., & Srianand, R. 2008a, A&A, 481, 327
- Noterdaeme, P., Petitjean, P., Ledoux, C., Srianand, R., & Ivanchik, A. 2008b, A&A, 491, 397
- Olive, K. A., & Skillman, E. D. 2001, New Astronomy, 6, 119
- Olive, K. A., Steigman, G., & Walker, T. P. 2000, Phys. Rep., 333, 389
- O’Meara, J.M., *et al.* 2001, ApJ, 522, 718
- O’Meara, J. M., Burles, S., Prochaska, J. X., et al. 2006, ApJ, 649, L61
- Penprase, B. E., Prochaska, J. X., Sargent, W. L. W., Toro-Martinez, I., & Beeler, D. J. 2011, ApJ, 721, 1
- Petitjean, P., Bergeron, J., & Puget, J. L. 1992, A&A, 265, 375
- Petitjean, P., Ledoux, C., Noterdaeme, P. and Srianand, R. 2006, A&A, 456, L9
- Pettini, M., & Bowen, D. V. 2001, ApJ, 560, 41
- Pettini, M., Zych, B. J., Murphy, M. T., Lewis, A., & Steidel, C. C. 2008, MNRAS, 391, 1499
- Pilachowski, C. A., Sneden, C., & Booth, J. 1993, ApJ, 407, 699
- Pinsonneault, M.H., Walker, T.P., Steigman, G., & Narayanan, V.K. 1998, ApJ, 527, 180
- Pinsonneault, M.H., Steigman, G., Walker, T.P., & Narayanan, V.K. 2002, ApJ, 574, 398
- Pospelov, M., & Pradler, J. 2010a, Annual Review of Nuclear and Particle Science, 60, 539
- Pospelov, M., & Pradler, J. 2010b, Phys. Rev. D, 82, 103514

- Pospelov, M., Pradler, J., & Steffen, F. D. 2008, *J. Cosmology Astropart. Phys.*, 11, 20
- Press, W. H., & Schechter, P. 1974, *ApJ*, 187, 425
- Prodanović, T., & Fields, B. D. 2008, *J. Cos. Astro-Particle Phys.*, 9, 3
- Rebolo, R., Beckman, J. E., & Molaro, P. 1988, *A&A*, 192, 192
- Richard, O., Michaud, G., & Richer, J. 2005, *ApJ*, 619, 538
- Rollinde, E., Vangioni, E., Maurin, D., Olive, K. A., Daigne, F., Silk, J., & Vincent, F. H. 2009, *MNRAS*, 398, 1782
- Rossi, S., Beers, T. C., & Sneden, C. 1999, *The Third Stromlo Symposium: The Galactic Halo*, 165, 264
- Ryan, S.G., Norris, J., & Beers, T.C. 1999, *ApJ*, 523, 654
- Ryan, S. G., Beers, T. C., Olive, K. A., Fields, B. D. & Norris, J. E. 2000, *ApJ*, 530, L57
- Safrank-Shrader *et al.* 2010, *ApJ*, 723, 1568
- Savage, B. D., Lehner, N., Fox, A., Wakker, B., & Sembach, K. 2007, *ApJ*, 659, 1222
- Sbordone, L., Bonifacio, P., Caffau, E., et al. 2010, *A&A*, 522, A26
- Schneider, R. & Omukai, K. 2010, *MNRAS*, 402, 429
- Sivarani, T., et al. 2004, *A&A*, 413, 1073
- Smith, B.D., Turk, M.J., Sigurdsson, S., O’Shea, B.W. and Norman, M.L. 2009, *ApJ*, 691, 441
- Spite, F. & Spite, M. 1982, *A&A*, 115, 357
- Spite, F., & Spite, M. 1986, *A&A*, 163, 140
- Spite, F., & Spite, M. 1993, *A&A*, 279, L9
- Spite, F., & Spite, M. 2010, *IAU Symposium proceedings, No 268, Geneva, Edts Charbonnel et al., Cambridge Un. press*, p. 201
- Spite, M., Spite, F., & Maillard, J. P. 1984, *A&A*, 141, 56
- Springel, V. and Hernquist L., 2003, *MNRAS*, 339, 312

- Thorburn, J. A. 1994, *ApJ*, 421, 318
- Tumlinson, J., Malec, A. L., Carswell, R. F., et al. 2010, *ApJ*, 718, L156
- Vangioni, E. & Audouze, J. 1988, *AA*, 193, 81
- Vangioni, E., Silk, J., Olive, K.A. & Fields, B. 2011 *MNRAS* 413, 2987
- Vauclair, S., & Charbonnel, C. 1998, *ApJ*, 502, 372
- Walker, T. P., Steigman, G., Kang, H.-S., Schramm, D. M., & Olive, K. A. 1991, *ApJ*, 376, 51
- Yang, J., Turner, M. S., Schramm, D. N., Steigman, G., & Olive, K. A. 1984, *ApJ*, 281, 493
- Yong, D., Lambert, D. L., & Ivans, I. I. 2003a, *ApJ*, 599, 1357
- Yong, D., Grundahl, F., Lambert, D. L., Nissen, P. E., & Shetrone, M. D. 2003b, *A&A*, 402, 985
- Yoshii, Y., & Saio, H. 1986, *ApJ*, 301, 587